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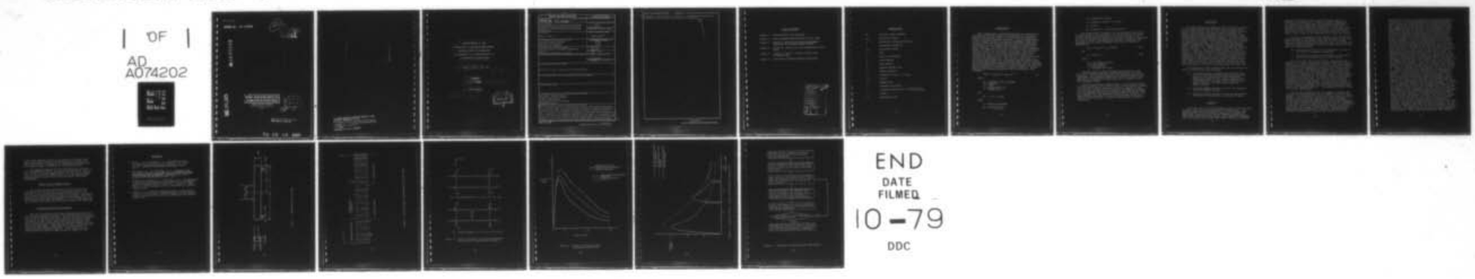

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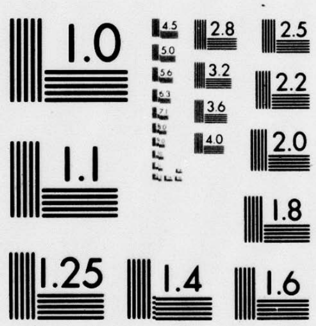


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# INVESTIGATION OF THE SUITABILITY OF THE BAZANT ENDOCHRONIC MATERIAL MODEL FOR MODELLING THE CONCRETE IN A SAMSON ANALYSIS OF A REINFORCED CONCRETE BEAM.

10 James W. Jeter, Jr., PhD

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This investigation involved evaluating the potential of the Bazant endochronic (plain concrete model as a possible avenue to an accurate model of the behavior of dynamically loaded reinforced concrete structures. A previous attempt to apply this model to the problem of a dynamically loaded beam was unsuccessful, due to an instability in the computer formulation of the model. In this study it was found that interaction between the tensile cracking model and the SAMSON nonlinear dynamic finite element structural analysis program used for the beam analysis problem resulted in inconsistent definition of the strain behavior experienced by CONT

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the material, thereby producing instability. A procedure was developed and demonstrated, which successfully eliminated the instability.

## LIST OF FIGURES

# NOMENCLATURE

| | |
|---|---|
| $dz$ | Intrinsic time increment |
| $e_{ij}$ | Deviatoric strain |
| $f$ | Hardening - softening function |
| $r$ | Horizontal coordinate |
| $s_{ij}$ | Deviatoric stress |
| $t$ | Time |
| $z$ | Vertical coordinate |
| $G$ | Shear modulus |
| $K$ | Bulk modulus |
| $P$ | Applied dynamic load |
| $Z_1$ | Bazant constant |
| $\varepsilon$ | Volumetric strain = $(1/3)\varepsilon_{kk}$ |
| $\varepsilon_{ij}$ | Strain |
| $\zeta$ | Damage term |
| $\lambda$ | Inelastic dilitancy |
| $\xi$ | Distortion measure ($d\xi = \sqrt{1/2\ de_{ij}\ de_{ij}}$) |
| $\sigma$ | Stress |
| $\tau_1$ | Relaxation time |

## INTRODUCTION

This investigation involved evaluating the potential of a promising nonlinear (plain) concrete model as a possible avenue to an accurate model of the behavior of dynamically loaded reinforced concrete structures. Typical applications of such a model would be to blast or earthquake loaded protective structures which may undergo significant permanent deformation and yet achieve their function of protection of their contents. This study was an extension of work begun during the summer of 1978 at the Air Force Weapons Laboratory (AFWL), Kirtland Air Force Base, New Mexico. The nonlinear concrete model to be considered is the endochronic model described by Bazant in the paper "Endochronic Theory of Inelasticity and Failure of Concrete" (1). Rather than assume a metal-like behavior with a well defined yield point, as plasticity based models do, or dealing with the complexities of a hypoelastic model, the endochronic model allows inelastic strains to accumulate gradually by characterizing the inelastic strain accumulation by a scalar parameter called intrinsic time, whose increment is a function of strain increments. Bazant develops the following expression for the intrinsic time parameter:

$$(dz)^2 = (d\zeta/Z_1)^2 + (dt/\tau_1)^2 \qquad (1)$$

where

$dz$ = intrinsic time increment
$Z_1$ = constant
$t$ = time
$\tau_1$ = relaxation time
$\zeta$ = damage term

and

$$d\zeta = f_1\,(\xi,\ \underline{\varepsilon},\ \underline{\sigma})d\xi$$

where

$\xi$ = distortion measure

$$d\xi = \sqrt{1/2\ de_{ij}\ de_{ij}}$$

$e_{ij}$ = deviatoric strain

$\underline{\varepsilon}$ = volumetric strain = $(1/3)\varepsilon_{kk}$

$\underline{\sigma}$ = stress

$f_1$ = hardening - softening function

The second term in equation (1) can be ignored for loads of short duration such as those to be considered in this study. If the strains are considered as the sum of volumetric components and deviatoric components, and each of these is expressed as a sum of elastic increments and inelastic increments, the components of the strain increments can for this study be expressed as

$$de_{ij} = ds_{ij}/2G + s_{ij}\ (dz/2G) \qquad (2a)$$

and

$$d\varepsilon = d\sigma/3K + d\lambda \qquad (2b)$$

where

$s_{ij}$ = deviatoric stress
G = shear modulus
K = bulk modulus
$\lambda$ = inelastic dilitancy

Suitable functions were developed by Bazant for $\lambda$ and $f_1$ so that inelastic concrete characteristics such as strain softening, cyclic loading behavior, and unloading behavior are reproduced. Experimental results for axial and biaxial loadings on plain concrete are duplicated quite accurately with the endochronic model

Adapting the Bazant concrete model to reinforced concrete structural members is not difficult if a finite element analysis is to be used. Either separate (discrete) elements can be used for the concrete and for the steel, or composite elements can be developed, where the structural properties of the steel are "smeared" into the adjacent concrete finite elements. The former method was chosen for this study because of its convenience and flexibility. Tensile cracking must be modelled separately.

## OBJECTIVES

Work done during the summer of 1978 involved an existing finite element program of the Bazant material model which had been developed at AFWL for use with the SAMSON nonlinear dynamic finite element structural analysis program (2). Several modifications were made to both the material model formulation and to the SAMSON program to facilitate running the nonlinear reinforced concrete problem. A limited tensile cracking model was used and steel reinforcement was included as separate bar elements. The analytical model was to be tested by comparing analytical results with experimental results obtained for a dynamically loaded beam by Feldman, Keenan, and Seiss (3). Characteristics of the test beam are shown in Figure 1. The finite element model is shown in Figure 2. Concrete covering for the reinforcing steel was omitted in the model. Details and results of this study are summarized in reference (4). The attempt to duplicate the experimental problem analytically was unsuccessful, due to instability in the Bazant material model as formulated for this computer analysis. This caused the analysis to stop after only about a tenth of the duration of the blast load. Contradictions in the tensile cracking model were observed.

The objective of this investigation was to continue this effort by considering the following:

(1) The existing finite element material formulation was to be studied and modified particularly with regard to the interaction of the endochronic compression model and the tensile cracking model. This study was to be done using a "driver" program to simulate the bulky, more expensive SAMSON program.

(2) The beam problem was then to be run to completion using the SAMSON program.

(3) Positive results in steps (1) and (2) above would then lead to refinements in the material model.

## ANALYSIS

The first step in this investigation was to study the data available from the effort described in reference (4). One possible cause of the instability seen in the analysis was conceivably the cracking of all the elements surrounding a node point, causing the node point, which could have considerable acceleration due to the large impact loading, to undergo

excessive deformation before sufficient forces would be developed to constrain it. However, analysis showed that the instability occurred when the program was operating on an element on the compressed portion of the beam, where extensive cracking would not be expected. The Poisson effect could have caused a horizontal crack, but the low stresses and strains in the vertical steel indicate that this did not occur. Thus, there is no indication of a "freed" node point.

In order to determine if the instability of the solution could possibly be developed in the material model itself, the model was studied extensively using the "driver" program. Two points became obvious for a material with one or more free surfaces loaded with applied strains (strains calculated from node point displacements);

(1) The applied strains are not necessarily related to the strains the material undergoes;

(2) The resulting stresses are dependent on how strain behavior is modelled across a free surface.

The first point can be explained by considering what happens to a single quadrilateral element when a crack occurs parallel to an edge, as shown in Figure 3. Material behavior in the direction perpendicular to the crack will be a function of strains in the orthogonal directions, not a function of applied strains in the direction perpendicular to the crack, since these cause only free body motion. The second point can best be illustrated by considering Figure 4, which shows stress-strain relations for an element loaded with increments of uniform uniaxial strain. For the load shown, different assumptions were made about the strains in the direction perpendicular to a free surface. In one case, the strain in that direction was assumed zero; the second case assumed an elastic Poisson adjustment; the third case adjusted for both elastic and inelastic behavior. The assumption chosen affects the results considerably.

The driver program was used to attempt to simulate the instability which developed for an element in the test beam program. A problem time at which the element behavior seemed normal, with no cracking, was taken as a starting point. Biaxial strains were then applied with strain increments in one direction increasing parabolically while strain increments in the other direction increased linearly, both in compression. It was felt that this loading would be similar to that which would occur in the beam. Three different approaches were considered and are compared in Figure 5. The differences between the approaches relate to the formulation of the

material model, which is described by the flow chart shown in Figure 6. The iteration portion of the material model is seen to begin with trial values of the stress increments and of the strain increments across free surfaces and ends with computed values of the same. It is important to note that SAMSON strains are based on nodal point motion, which doesn't reflect material behavior if free surfaces exist. An accurate solution requires that the strains at the end of the last load step be representative of the material behavior. Convergence may not occur if the initial trial strain increments are a poor approximation of the computed strain increments. The trial strain increments were found in different ways for the three approaches. In the first approach, which corresponds to the method used in reference (4), the strain at the end of the last time increment were corrected for free surfaces in the material model in the previous load step. A trial value for the strain increments is then found by subtracting these strains from the strains SAMSON produces for the end of the current load step. This approach finds the strain increments by subtracting strains which are incompatible if free surfaces exist: the strains existing in the material, which account for free surfaces, and the SAMSON strains, which are based on node point movement, and ignore free surfaces. Thus, the resulting trial values produced for the strain increment may be such a poor approximation of the computed values, that convergence doesn't occur, as, indeed is the case for this approach, as seen in Figure 5. A means of avoiding this divergence was suggested by personnel at AFWL, who were concerned with an axisymmetric problem. They noted that if strains are not redefined at the end of the material model, convergence occurs. This approach utilizes the material model to determine stresses only, based on the strains defined by the SAMSON program. However, no adjustment is then made for free surfaces, which are not correctly presented by the SAMSON program. The result is a satisfactory solution for axisymmetric problems if no free surfaces occur, but not for problems with free surfaces. The results of such an approach are also shown in Figure 5. Convergence occurs, apparently because trial strain increments are reasonably compatible with computed strain increments, since the trial values are found by subtracting one set of SAMSON strains from another. Clearly, the resulting stress values will be inaccurate, since free surfaces are never accounted for and are, in fact, treated as constrained surfaces. The strains perpendicular to the surface are thus defined incorrectly when used to compute stresses. The third approach considered accounted for the free surfaces and yet converges. The strains at the end of the current load step produced by the SAMSON program are adjusted approximately for free surfaces. Trial strain increments are then computed

using these adjusted values at the end of the current load step and adjusted values at the beginning of the load step. These trial strain increments are reasonably compatible with the computed strain increments, so convergence occurs.

This modified version of the Bazant model was inserted into the SAMSON structural analysis program which was then set up to study the Feldman beam problem. At the time of expiration of this grant, the SAMSON analysis of the Feldman beam problem had been begun and is to be continued under other arrangements.

## STATUS OF THE RESEARCH EFFORT

The Bazant material subroutine has been studied and modified so that it provides an accurate depiction of the behavior of the material as applied to free surfaces, and yet no longer has an inherent tendency to diverge. The SAMSON analysis of the Feldman beam problem has been begun and is to be continued under other arrangements. The cracking model has been studied and appropriate modifications have been suggested.

## CONSULTATION WITH AFWL PERSONNEL

Work on this project was coordinated with personnel from the Structural Dynamics Section, Civil Engineering Division of the Air Force Weapons Laboratory. Several telephone discussions took place in the course of the effort and one trip was made to AFWL on 12 April 1979, where extensive discussions took place concerning the desired and the apparent behavior of the Bazant material model. Participating in these discussions were the author and Messers Donald Cole, Project Engineer, and Douglas Seemann, Research Engineer. This effort will be continued by the author at AFWL during the summer of 1979.

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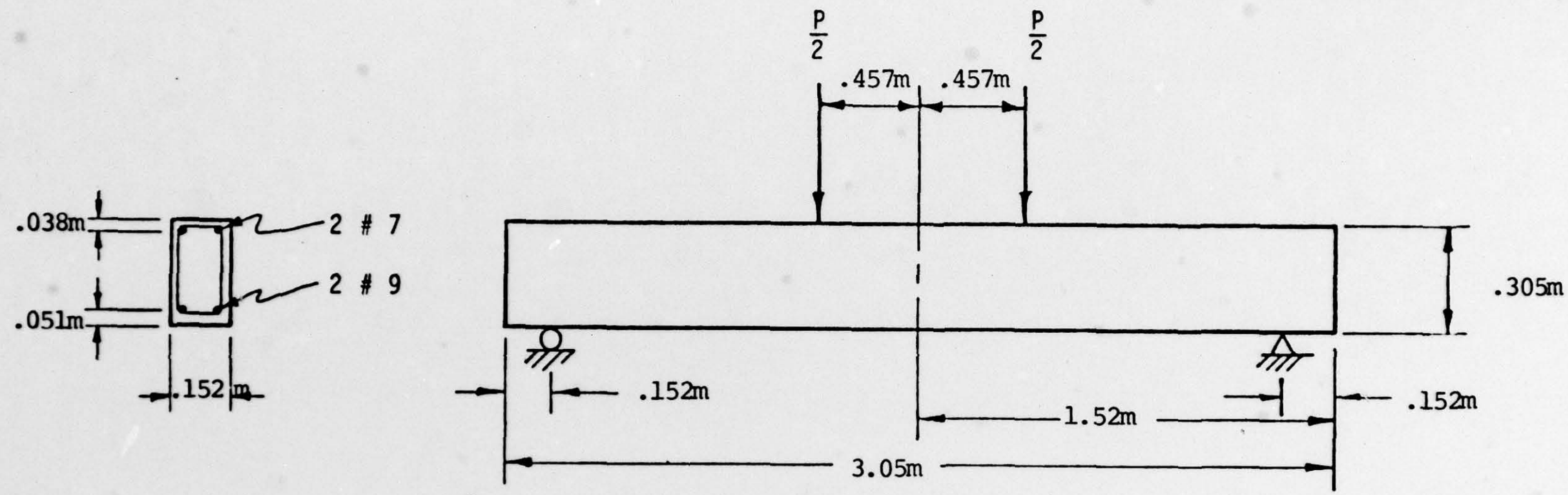



Figure 1. Characteristics of Test Beam

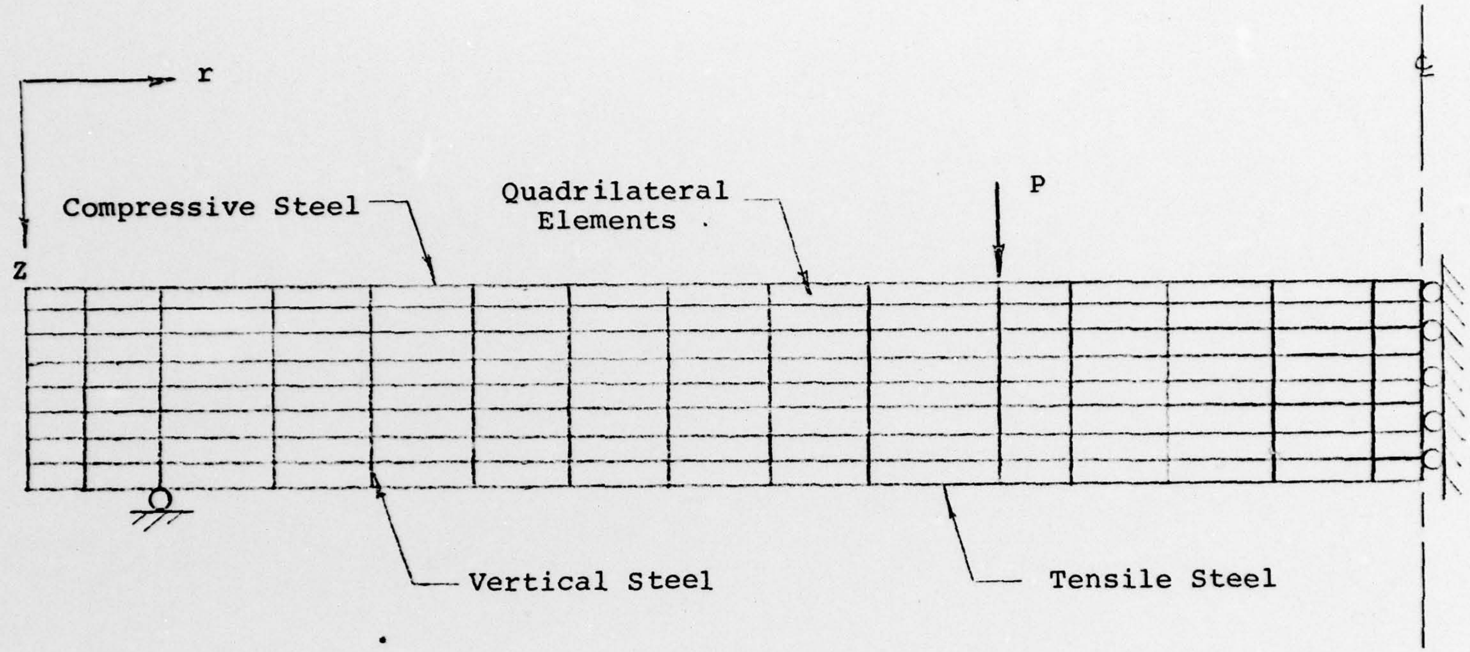
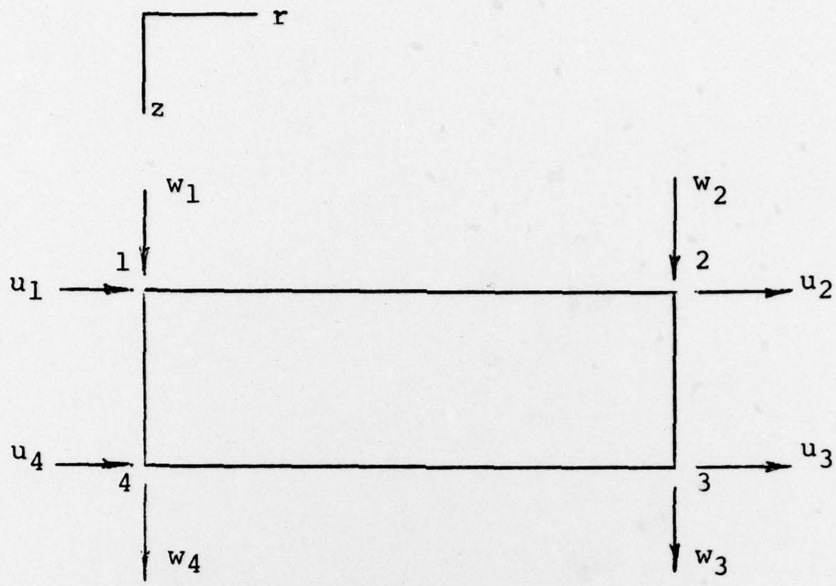
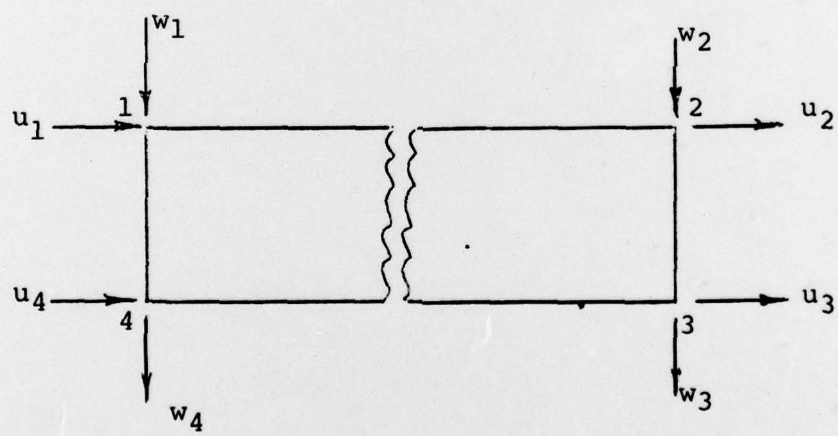



Figure 2. Finite Element Representation of Test Beam




(a) Uncracked Element ($\varepsilon_r = f[u_1, u_2, u_3, u_4]$)




(b) Cracked Element ($\varepsilon_r \neq f[u_1, u_2, u_3, u_4]$)

Figure 3. Effect of Cracking on Strain-Displacement Relations for a Quadrilateral Element

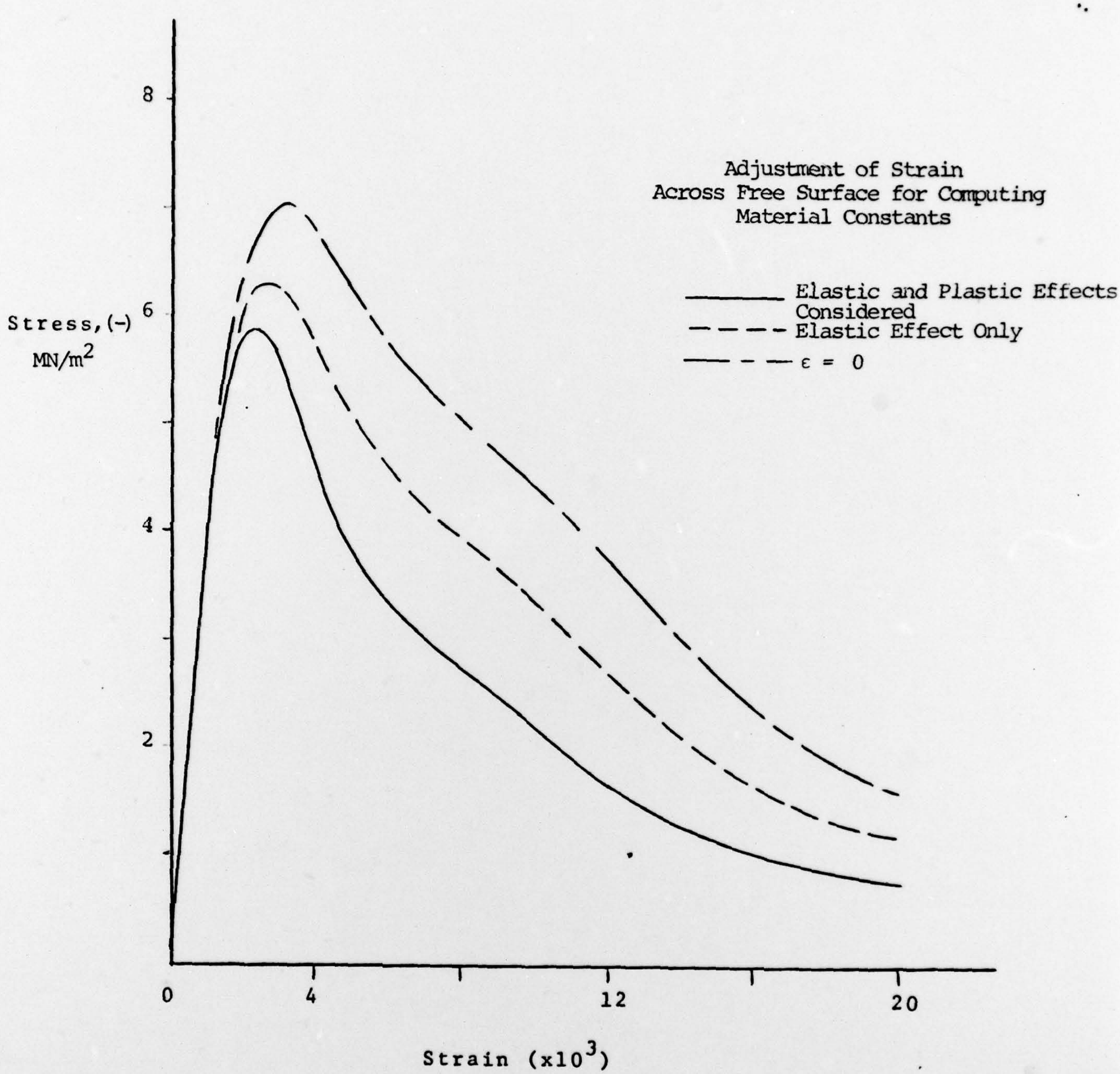



Figure 4. Stress vs. Strain For One-Dimensional Strain Load

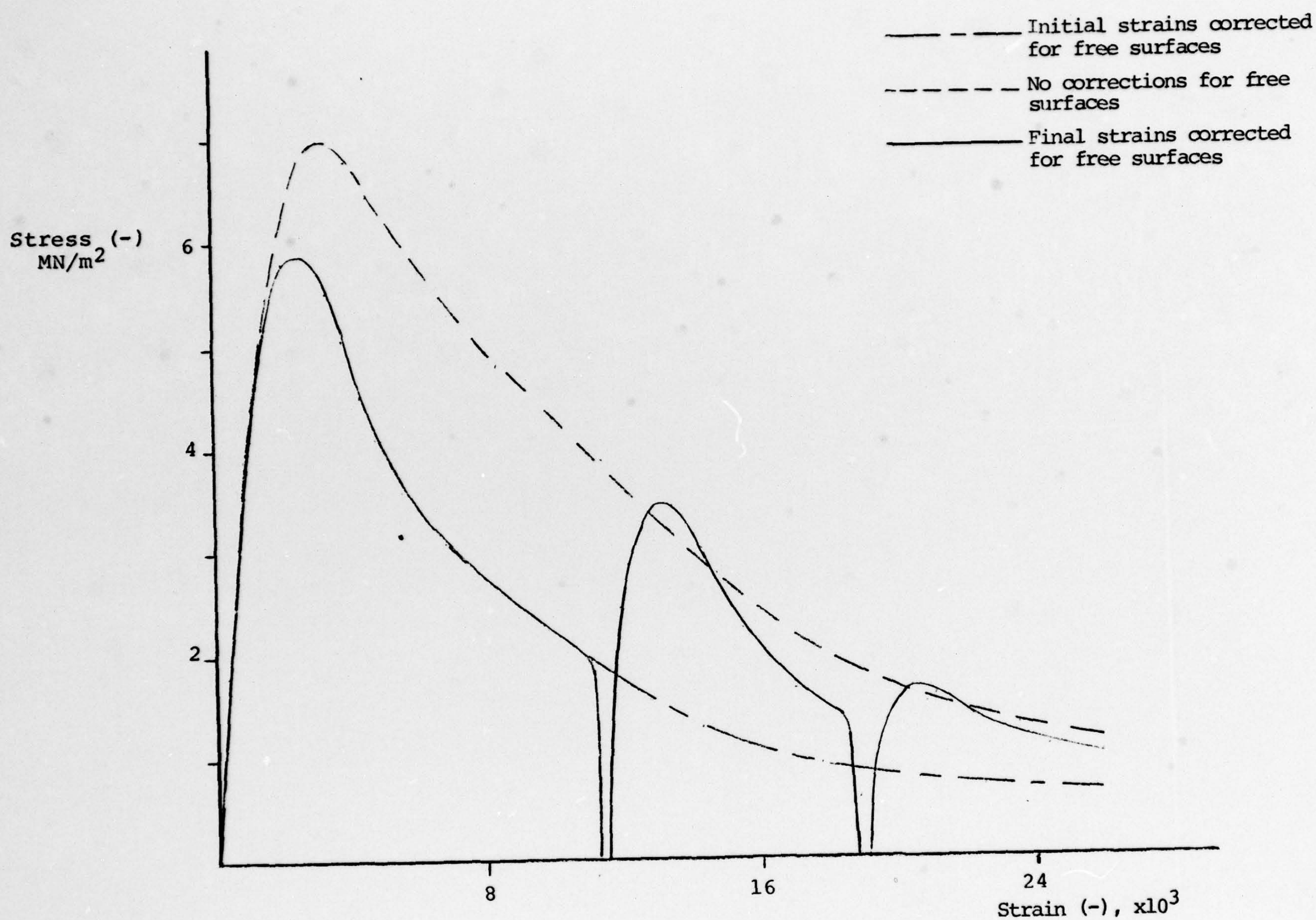



Figure 5. Stress vs. Strain - Biaxial Loading With In-plane Crack

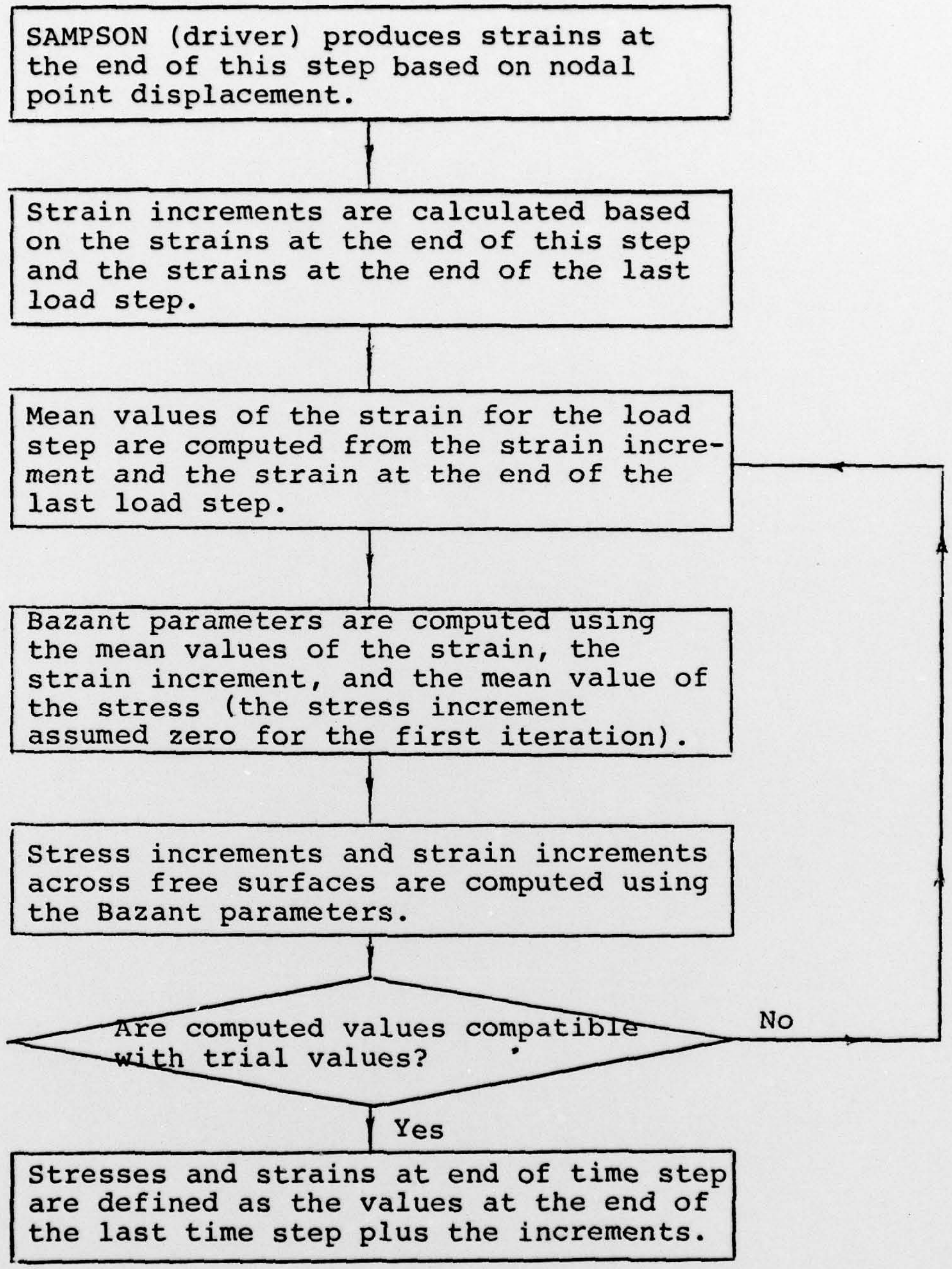



Figure 6. Flow Chart of Material Model Formulation